A REVIEW OF THE FREQUENCY AND TIMING ACTVITIES AT THE JET PROPULSION LABORATORY

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ABSTRACT

The Jet Propulsion Laboratory is the NASA Lead Center for research, development, implementation, and testing of frequency and timing systems. The spectrum of activities at JPL span from research and development in the areas of precise frequency sources and distribution systems to testing and implementation of time and frequency subsystems in NASA's Deep Space Network (DSN). These activities are carried out by two groups, one broadly engaged in R&D, and the other in engineering and implementation of F&T systems. Current activities in the R&D areas include the development of a Trapped Mercury Ion frequency standard, Superconducting Cavity Stabilized Maser, Hydrogen maser, and fiber optic time and frequency distribution networks. The engineeering and implementation activities include the installation of the new MARK IV Timing Subsystem in the DSN, the development and installation of techniques and methodology for precise time synchronization for the DSN, and the operation of the Frequency Standards Test Laboratory. In October of 1985 the two groups were located in a new facility which houses all the frequency and timing personnel and laboratories, including a unique test facility for characterization of the performance of all frequency standards, time and frequency equipment and components. In this paper details of the activities in frequency and timing at JPL will be presented.

INTRODUCTION

NASA's Deep Space Network (DSN) is a communication network consisting of three complexes located in California, Spain, and Australia. All spacecraft interplanetary navigation and communications are carried out through the DSN. The Jet Propulsion Laboratory (JPL) has the responsibility of managing the Deep Space Network for NASA. The DSN's requirements for precise frequency and timing are some of the most stringent placed on this technology. These requirements arise from the need for precise spacecraft navigation and position location, as well as certain radio science experiments such as Very Long Baseline Interferometry (VLBI) and gravitational wave detection. Because of the significance of the Frequency and Timing Subsystem (FTS) to the operation of the DSN, JPL has been assigned the role of NASA Lead Center for Frequency and Time.

The activities at JPL in the area of frequency and timing are extensive and quite comprehensive. They span the entire spectrum of efforts on research and development, specification and

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implementation, and testing and characterization. These activities are carried out by two technical groups: the Time and Frequency Systems Research Group, and the Frequency and Timing Systems Engineering Group. The personnel, the laboratory, and testing facilities of the two groups are co-located in a new Frequency Standards Laboratory at JPL. The proximity of the two groups ensures that the R&D efforts are planned in response to, and with cognizance of, the needs of the implementation group. It further ensures that the implementation group has cognizance and direct access to state-of-the-art frequency and timing devised by the R&D group. In this manner a close working relationship and interdependence is maintained between the two groups, the result of which is an efficient and effective support for the frequency and timing needs of the DSN.

This paper outlines the activities of the two technical groups involved in frequency and timing at JPL. The first two sections of the paper review the activities of the R&D and the implementation groups separately. Each section provides information on the scope of recent activities, as well as efforts planned for the future. Because the intent of this paper is to provide a description of the scope of the work, technical details will be, for the most part, excluded from the two sections; the reader is referred to the literature for further details. A third section will provide a description of the new Frequency Standards Laboratory, which is a unique facility housing the activities of the two groups. A novel feature of this facility is the capability for comprehensive testing and characterization of all FTS-related components, equipment, and systems.

RESEARCH AND DEVELOPMENT

The program of R&D at JPL includes efforts directed toward generation of precise frequency and time, the distribution of reference signals to remote locations, analysis and modeling of oscillator noise, and development of equipment and techniques for testing and characterization of the stability of a Deep Space Station located at the California site.

The development of precise sources of frequency is an all-encompassing activity which includes the development of techniques and components to improve the reliability and performance of the hydrogen maser, the development of a trapped mercury ion standard, and the development of ultra-stable cryogenic oscillators.

The hydrogen maser program is directed towards the need to improve the stability and the reliability performance of this device, which is currently the primary reference in the DSN. This program consists of efforts at the Applied Physics Laboratory of the Johns Hopkins University, under contract to JPL, to develop various sources, optics, cavities, electronic circuitry, and other components with the potential of improving the maser performance. The details of this effort are reviewed in a separate paper in these proceedings [1] and thus will not be elaborated further here.

Another R&D contract with the Smithsonian Astrophysical Observ-

atory(SAO), the major manufacturer of hydrogen masers for the DSN, is directed towards the implementation of the of Adiabatic Fast Passage (AFP) technique. This technique is designed to reduce the number of hydrogen atoms in the undesired hyperfine state which do not interact with the state-selecting magnet, and enter the storage bulb to produce a frequency shift in the H-maser signal. AFP utilizes a direct current magnetic field parallel to the hydrogen beam, and a radio frequency magnetic field perpendicular to it. The result of the interaction of the atom with the two fields is a slow precession of the atomic spin and its inversion to a state which can subsequently be deflected out of the beam with a second state selecting magnet. A hydrogen maser will be fitted with the AFP equipment, and its performance will be evaluated in 1987.

The R&D activities in the ion confinement technology is directed towards the development of a microwave oscillator based on trapped mercury isotope 199 ions [2]. Such a source will have a resonance frequency at 40.5 GHz, corresponding to the frequency associated with the hyperfine level splitting of the ground state of the singly ionized mercury. Because of this relatively large frequency, the atomic line Q is correspondingly large, thereby offering the potential for improved frequency stability. In the past three years efforts at JPL have led to the development of the physics and the electronics packages of a trapped ion device for a laboratory demonstration. These efforts culminated in the integration of the physics package and the microwave electronics, and the subsequent demonstration of this device operating in the open loop mode, in the last quarter of 1986. The closed loop demonstration of a trapped mercury ion frequency standard is scheduled for the summer of 1987, and is expected to have a stability superior to cesium beam standards. The group has a long-term plan of exploiting this technology and developing standards based on ion confinement which will yield fractional frequency stabilities in the parts in 10^{-17} range for averaging intervals of 10^4 seconds.

The development of cryogenic oscillators is another extensive activity in which the R&D group is engaged. Investigations during the past three years have produced an all-cryogenic superconducting maser with the potential for yielding stabilities of part in 10^{-18} for averaging intervals of a thousand seconds. This device has the potential for the highest spectral purity, and may find application as a flywheel for a trapped ion device for the production of stabilities in the parts in 10^{-17} range for short, medium, and long averaging intervals. Recent progress in this area is detailed in a separate paper in the proceedings of this conference [3].

A second type of cryogenic oscillator is under development at APL. This device, termed the supercooled quartz oscillator, is based on the high Q's that have been observed at low temperatures for quartz resonators. Current efforts at APL are directed towards the characterization of this low temperature behavior toward the development of an oscillator. Aside from high-spectral purity, a supercooled quartz oscillator may also be used as the flywheel for the trapped ion standard.

The distribution of precise time and frequency is a crucial segment of the frequency and time requirements of the DSN. The distribution network should ensure that the precise signals produced by sources of time and frequency are not degraded while enroute to various local and remote users. Beyond this, the capability of the distribution network to service various users directly influences the efficiency and the economy of the Frequency and Timing Subsystem (FTS) in the DSN. Because of the significance of the distribution capability for precise time and frequency, considerable effort has been expanded in the past few years to exploit technologies capable of meeting associated requirements. In particular, efforts have been directed towards the development and implementation of components and systems that enable the use of optical fibers as the medium of distribution for precise signals. Recently, a 14 km link with a measured stability of 1.5 x 10^{-15} at a 1000 second averaging time was demonstrated in the Goldstone complex for a single mode optical fiber, in a cable buried 1.5m in the ground. Results of measurements carried out in this demonstration indicate that increased stabilities of two orders of magnitude may be achieved additionally through stabilization of the link to compensate for phase and frequency shifts produced by temperature variations and other effects. Details of this work and their implications are presented in this conference in a separate paper [4], to which the interested readers are referred.

Other activities of the Time and Frequency Systems Research Group include the development of improved hardware, software, and statistical algorithms for frequency stability measurement. A maximum likelihood approach to the N-cornered hat problem is under study. Recently a scheme has been developed to utilize a commercial time interval counter and appropriate software to measure Allan sigmas without the need for expensive and specialized digital hardware. Experiments using simulated data have indicated an improved noise floor for a system utilizing this scheme. Details of this work will be presented elsewhere [5].

IMPLEMENTATION

During the recently completed implementation of the Deep Space Network over the last several years, JPL has essentially developed, and purchased a complete new Frequency and Timing Subsystem (FTS). This includes six SAO Hydrogen Masers and ten Cesium Beam frequency standards. The Hydrogen Maser is the prime frequency standard at each of the three DSN sites in California, Spain and Australia, with a second Hydrogen Maser as an operating spare. Two Cesium Standards at each site are used as frequency and timing comparison devices and additional spares.

Equipment was developed at JPL to synthesize and distribute Hydrogen Maser stability reference signals to many users in each deep space station of every site. These consist of nine synthesized frequencies with a total of 225 outputs. This equipment is designed to preserve the Hydrogen Maser stability characteristics.

Triple redundant digital timing clocks were purchased from industry with distribution to each individual user (approximately 50 per site) using individual time code translators for time code and rate pulses.

Feedback stabilized reference frequency distribution equipment was developed at JPL to distribute reference signals to the antenna area preserving the Hydrogen Maser stability for Radio Science and VLBI experiments. Comb-tone generators are a part of this equipment, and were used to inject a comb tone spectrum into the S and X band antenna feedhorns for receiver phase calibration purposes. In addition, a phase stabilized 20 MHz, CW signal, is available in the antenna. This stable 20 MHz is intended for frequency multiplication to S- and X-Band.

Global Positioning System (GPS) time synchronization receivers are currently installed at all three sites. This capability is to provide a state of the art time and frequency synchronization on an intercontinental basis to approximately 50 nanosecond uncertainty to the Spanish and Australian sites, and several nanoseconds from the California site to the National Bureau of Standards in Boulder, Colorado.

Computerized status monitoring capability has been incorporated to determine status of all Frequency and Timing Subsystems (FTS) assemblies at the site-centralized Monitor and Control console. With this capability, the console operator very quickly determines which frequency standard is prime (in use) and locates any FTS replaceable assembly equipment failure.

Several other tasks are currently in process. NASA's Voyager Spacecraft Project, Neptune Encounter Radio Science Occultation experiment has phase noise specifications which tax the state of the art's best crystal oscillators when mounted in the antenna and phase locked to the prime Hydrogen Maser in the control room building. In addition, the associated problems of increased phase noise due to antenna vibration has presented an interesting challenge of how to attenuate the vibration induced phase noise below the background from 1 Hz to greater than 10 KHz. The requirement is to distribute 100 MHz in the antenna from the hydrogen maser with the Allan variance stability performance of 1E-15 from 1000 to 3600 seconds and phase noise of -92dBc at 1 Hz from the carrier and following the typical F^{-3} slope for close-in phase noise. Responses with power-line related and other spurious interferences, must be below the background phase noise when measured in a 1 Hz bandwidth. The principal users of this 100 MHz are the receiver X-Band first local oscillator and the X-band exciter and transmitter pair. This task was started approximately six months ago and the first field installation is scheduled for June, 1988.

Semi-automated Allan variance measurement equipment is being designed to simultaneously measure three input channels. These are between the two hydrogen masers, the complete X-Band Radio receiver from the feedhorn to the detected output, and across the X-Band transmitter and associated exciter. This equipment is developed specifically for Project Galileo's Gravitational Wave Experiment. This equipment will be used to determine if the transmitter, receiver and prime hydrogen maser meet the 1000-to 3600-second stability specification for the experiment. This task has been started recently and is scheduled for completion in 1989.

Work continues on the DSN intercontinental time synchronization using the GPS satellite. Kalman filter techniques are being added to the data reduction techniques. Currently, data is acquired by telephone modems using NASA overseas voice links to the sites. In the future, data will be transmitted to JPL via commercial satellite links, which are currently used by JPL to transmit their transoceanic site data.

Future tasks include the automated monitoring of all clocks, frequency offset of DSN site standards, and other health functions. These will be transmitted to JPL over the same satellite link as the future time synchronization data. All will be transmitted to JPL from the three sites in near real time for analysis and reporting purposes.

The Frequency and Timing Systems Engineering Group purchases and installs the hydrogen masers, and maintains six units installed at the three sites. JPL has been purchasing a new hydrogen maser from SAO every 1-2 years for the past seven years. As part of this task, all hydrogen masers and other frequency standards and related equipment are maintained, tested and evaluated in a special environmentally-controlled test area at JPL. Environmental chambers are a part of this laboratory, characterizing the appropriate temperature, barometric pressure and humidity range in which this equipment is expected to perform. For magnetic field testing, a seven foot diameter helmholtz coil is used to vary the ambient magnetic field. Instrumentation includes multiple channels of Allan variance measurement capability, Fast Fourier Transform (FFT) phase noise measurement capability, phase offset recording equipment, and many channels of diagnostic equipment. An HP 1000-A700 computer is currently being prepared and programmed to augment this equipment by automating most of the data acquisition and reduction process. Continuous power is included to prevent interruption of data acquisition during long-term (several month) testing.

FREQUENCY STANDARDS LABORATORY

In 1985, NASA/JPL completed a new Frequency and Timing Laboratory for all frequency and timing research and implementation tasks. This is a 14,400 square foot single-story facility with offices for 22 personnel, and three laboratories. The three laboratories are: a 2200 square foot Physics area, a 2200 square foot Implementation area, and a 2500 square foot specialized environmentally controlled test area. The first two laboratories are used for atomic frequency standard research and electronic design. A small machine shop is included as an ancillary room for prototype purposes.

The Research and Development Laboratory houses R&D projects such as Trapped Ion Standard, fiberoptics, and the Superconducting Cavity Oscillator, and the Hydrogen Maser Physics unit development and maintenance area. Included are several optical tables, cryogenic and vacuum equipment, a chemical hood and processing ovens. This laboratory is equipped with a concrete floor for maximum vibration stability of the optical tables and the Superconducting Cavity Oscillator.

The Implementation Laboratory is for electronic development and fabrication of FTS equipment for the DSN. Included in this room are electronics for

computer Monitor and Control; reference frequency synthesis and distribution; DSN time synchronization; and a digital clock with associated distribution equipment. Also included is a raised computer floor with positive air pressure which provides the same type of air conditioning as used at all DSN sites. This provides air conditioning for equipment cabinets under conditions similar to those those used in the DSN.

This environmentally-controlled test laboratory consists of 2500 square feet of floor space which is temperature controlled to an approximate 23 degree Celsius setpoint plus or minus 0.05 degrees. A computer floor is used throughout this area, and again the floor is positively pressurized to simulate a floor-to-ceiling "air curtain" with many vents in both the raised floor and ceiling. Redundant air handlers (conditioning equipment) are provided to maintain reasonable temperature control when a unit fails or requires maintenance. All reinforcing rods ("rebar") are stainless steel to reduce the earth's magnetic field variations due to permability changes caused by fluctuating outside temperature. All electrical conduit, piping, and other metallic building materials are also non-magnetic.

Three non-magnetic environmental chambers were built into this laboratory. Each chamber is 8x8x8 feet, and each is a combined temperature, barometric pressure and humidity chamber. Each is separately controlled and independent. Any frequency standard or associated equipment may be tested for the characteriziation of the above parameters with these environmental chambers.

In order to provide continuous power, 14 KVA of uninterruptible power is available. In addition, a 300KVA natural gas power plant is installed which starts automatically should the commercial power ever fail.

SUMMARY

Several activities are currently underway at the Jet Propulsion Laboratory in the frequency and timing systems. The development of the sources of precise frequencies includes work on the hydrogen maser, the trapped mercury ion standard, and cryogenic resonators. Precise frequency and time distribution systems are also under development based on fiber-optic systems. These activities are supported by the development of techniques, equipment, and methodologies that allow characterization of the stability and noise.

The implementation of frequency and timing systems is also on-going with efforts directed towards precise synchronization of stations via the GPS system, computerization of the status monitoring capability, automation of the Allan variance measuring equipment, and the distribution of stable and low phase noise 100 MHz signals to the antenna.

The activities of the groups involved with the above is carried out in a new Frequency Standards Laboratory facility which houses offices and labs. This facility also houses the test and characterization laboratory which is equipped with unique instruments and environmental chambers. A comprehensive testing and characterization of the stability of all frequency standards and associated components and equipment is possible with this capability.

The present and future efforts at the Jet Propulsion Labratory will ensure that the frequency and timing requirements of the Deep Space Network continues to support the various missions and science activities.

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